Applied Energy 191 (2017) 436–453

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Thermodynamic analysis and preliminary design of closed Brayton cycle using nitrogen as working fluid and coupled to small modular Sodium-cooled fast reactor (SM-SFR)

Olumide Olumayegun [a], Meihong Wang [a,*], Greg Kelsall [b]

[a] Department of Chemical and Biological Engineering, The University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom
[b] GE Power, Newbold Road, Rugby CV21 2NH, Warwickshire, United Kingdom

HIGHLIGHTS

- Nitrogen closed Brayton cycle for small modular sodium-cooled fast reactor studied.
- Thermodynamic modelling and analysis of closed Brayton cycle performed.
- Two-shaft configuration proposed and performance compared to single shaft.
- Preliminary design of heat exchangers and turbomachinery carried out.

ARTICLE INFO

Article history:
Received 11 September 2016
Received in revised form 13 January 2017
Accepted 29 January 2017
Available online 7 February 2017

Keywords:
Sodium-cooled fast reactor
Closed Brayton cycle
Nitrogen working fluid
Thermodynamic analysis
Heat exchanger design
Turbomachinery design

ABSTRACT

Sodium-cooled fast reactor (SFR) is considered the most promising of the Generation IV reactors for their near-term demonstration of power generation. Small modular SFRs (SM-SFRs) have less investment risk, can be deployed more quickly, are easier to operate and are more flexible in comparison to large nuclear reactor. Currently, SFRs use the proven Rankine steam cycle as the power conversion system. However, a key challenge is to prevent dangerous sodium-water reaction that could happen in SFR coupled to steam cycle. Nitrogen gas is inert and does not react with sodium. Hence, intercooled closed Brayton cycle (CBC) using nitrogen as working fluid and with a single shaft configuration has been one common power conversion system option for possible near-term demonstration of SFR. In this work, a new two shaft nitrogen CBC with parallel turbines was proposed to further simplify the design of the turbomachinery and reduce turbomachinery size without compromising the cycle efficiency. Furthermore, thermodynamic performance analysis and preliminary design of components were carried out in comparison with a reference single shaft nitrogen cycle. Mathematical models in Matlab were developed for steady state thermodynamic analysis of the cycles and for preliminary design of the heat exchangers, turbines and compressors. Studies were performed to investigate the impact of the recuperator minimum terminal temperature difference (TTD) on the overall cycle efficiency and recuperator size. The effect of turbomachinery efficiencies on the overall cycle efficiency was examined. The results showed that the cycle efficiency of the proposed configuration was comparable to the 39.44% efficiency of the reference cycle. In addition, the study indicated that the new configuration has the potential to simplify the design of turbomachinery, reduce the size of turbomachinery and provide opportunity for improving the efficiency of the turbomachinery. The findings so far revealed that the proposed two-shaft CBC with nitrogen as working fluid could be a promising power conversion system for SM-SFRs near-term demonstration.

1. Introduction

Generation IV nuclear reactors (Gen IV reactors) are the next step in the deployment of nuclear power generation to meet the world's future energy demand [1]. Of all the six Gen IV reactors, sodium-cooled fast reactor (SFR) has been identified as the most matured and hence the most suitable for near-term demonstration [2–4]. In addition to the larger SFRs, Small Modular Sodium-cooled Fast Reactors (SM-SFRs) with plant size ranging from 50 to 300 MWe are also under consideration by Gen IV International Forum (GIF) [5]. Generally, small modular reactors (SMRs) are

* Corresponding author.
E-mail address: wang_2003_uk@yahoo.co.uk (M. Wang).

http://dx.doi.org/10.1016/j.apenergy.2017.01.099
0306-2619/

Nomenclature

Abbreviations

2-D	two-dimensional
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
CBC	closed Brayton cycle
CDT	compressor-driving turbine
FPT	free power turbine
Gen IV	Generation IV
GIF	Gen IV International Forum
HPC	high pressure compressor
IHX	intermediate heat exchanger
LMTD	logarithmic mean temperature difference
LPC	low pressure compressor
Na/N_2 IHX	sodium/nitrogen intermediate heat exchanger
NIST	National Institute of Standards and Technology
PCHE	Printed Circuit Heat Exchanger
PCS	power conversion system
s-CO_2	supercritical carbon dioxide
SFR	sodium-cooled fast reactor
SM-SFR	small modular sodium-cooled fast reactor
SMR	small modular reactor
TTD	terminal temperature difference

Symbols

A	area (m^2)
AR	aspect ratio
b_H	blade height (m)
c	blade chord (m)
C	absolute velocity (m/s)
C_L	lift coefficient
Cp	specific heat capacity at constant pressure
D	diameter (m)
DF	diffusion factor
$dHaller$	de Haller number
d_s	specific diameter
f	Darcy friction factor
g	gravitational acceleration (m/s^2)
H	head (m)
h	specific enthalpy (kJ/kg) or convective heat transfer coefficient [W/(m^2 K)]
k	thermal conductivity [W/(m K)]
L	length (m)
ln	natural logarithm
$\dot{m}$	mass flow rate (kg/s)
min	minimum
n_s	specific speed
N_b	number of blade
Nu	Nusselt number
op	optimum value
P	pressure (Pa or N/m^2)
Pr	Prandtl number
$\dot{Q}$	volumetric flow rate (m^3/s)
Q	heat duty (watt or J/s)
r	radius (m)
Re	Reynold number
s	blade spacing (m)
T	temperature (K)
t	conduction length (m)
U	overall heat transfer coefficient [W/(m^2 K)] or blade velocity (m/s)
V	velocity (m/s)
W	power (W or J/s) or relative velocity (m/s)
α	absolute velocity angle (degree)
β	relative velocity angle (degree)
Δ	change in quantity
δ	fluid deflection through blade
ε	effectiveness or pipe roughness
η	efficiency
Λ	reaction
μ	viscosity (Pa s)
ξ	relative pressure loss or blade nominal loss coefficient
π	pressure ratio or pi
ρ	density (kg/m^3)
σ	blade solidity
ϕ	flow coefficient
ψ	stage loading coefficient
ω	rotational speed (rev/s)

Subscripts

0	stagnation property
1	turbine or compressor stage inlet
2	turbine rotor or compressor stator inlet
3	turbine or compressor stage exit
ad	adiabatic
C	compressor
c	cold stream
$elec$	electrical
ex	exit
gen	generator
h	hot stream or hydraulic
HX	heat exchanger
i	inlet
is	isentropic
N_2	nitrogen
Na	sodium
m	melting or mean-line
max	maximum
o	outlet
P	pump
RX	reactor
T	turbine or temperature
tt	total-to-total
x	axial component
θ	tangential component

viewed to have less financial risk, cheaper when mass produced, could be deployed faster, and are easier to operate and maintain compared with larger nuclear reactor [6,7]. Most of the components could be factory-built and then assemble on site. In addition, SMRs are more flexible with respect to their generation and location due to their lower capacity. Therefore, SMRs could help cope with the challenge of intermittent renewable energy by rapidly increasing or decreasing power output [8–11]. Also, it can be sited in off-grid areas requiring small power and future growth can be accommodated by simply adding extra units.

The power conversion system (PCS) implementation is critical to the successful commercialization of the SM-SFR power plant technology. The current SFRs (e.g. Phenix, SuperPhenix, BN 600, BN 800, etc.) adopt the proven Rankine steam cycle as PCS [12,13]. However, there are concerns over the coupling of steam cycle to SFR. The challenges include: (1) safety concern because